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Review

Disruptive innovations and decentralized renewable energy systems in Africa: A socio-technical review

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ABSTRACT

The adoption of decentralized renewable energy technologies (RTech) is a challenge in rural sub-Saharan Africa (SSA) despite their potential to increase the living standards of people in these areas. RTech such as solar photovoltaics, biogas digesters and improved cook stoves are disseminated in SSA to supply affordable energy, reduce indoor air pollution, combat deforestation and climate change. Despite extensive research and development in facilitating dissemination over the past five decades, significant challenges still hamper the adoption and sustainability of RTech. This paper reviews current literature on RTech adoption in SSA from a socio-technical perspective to examine the relationship between RTech and users. Three attributes of innovation (i.e., relative advantage, compatibility and complexity) are used to examine user behavior during RTech adoption. In this study, we examine whether and how the attributes of innovation generate disruptions in adopters' daily lives and how these changes influence the adoption decision process. This is particularly important in rural SSA because it reveals the appropriateness of RTech from different and sometimes interrelated perspectives. The study found that RTech adoption is likely to be high when benefits (i.e., lighting, short cooking times and income savings) are immediate and easily understood. However, RTech compatibility changes with adopter socio-economic status, especially when benefits such as lighting are highly valued. With more than half of the studies reviewed investigating only one innovation attribute, this paper makes a significant contribution to the literature by adopting a multi-dimensional analytical approach.

1. Introduction

The adoption of off-grid or decentralized renewable energy technologies (RTech), such as solar photovoltaics (PV), biogas digesters and improved cook stoves (ICS), is seen as a solution to reducing the effects of poverty especially in rural communities in sub-Saharan Africa (SSA) where it is not technically nor economically feasible to be connected to the national electric grid [1,2]. RTech provides clean energy that could facilitate income generation, reduce indoor air pollution and deforestation. Nevertheless, access to clean energy, especially for lighting and cooking, continues to be a significant challenge in SSA. With 30 out of 47 least developing countries located in SSA, about 657 million people in this region use biomass (such as firewood, agricultural residue and cow dung) to meet their basic energy needs [3,4]. The burning of biomass is thermally inefficient and produces smoke emissions that causes respiratory diseases such as tuberculosis, bronchitis and pneumonia [4,5]. The over-reliance of biomass, especially firewood and charcoal, also leads to deforestation [6] which is a major contributor to climate change [7]. Whilst the adoption of RTech is one of the solutions to extreme poverty and the detrimental health and environmental effects of using biomass for cooking, its adoption has been relatively slow in SSA. Understanding the factors influencing the slow adoption and subsequent diffusion of RTech at the household or community level is crucial for the provision of clean energy services and poverty alleviation.

In Innovation Diffusion Theory (IDT), Rogers [8] defines adoption as the decision for the "full use of an innovation as the best course of action available" (pg. 177). He [9] further defines diffusion as "a process by which alteration occurs in the structure and functions of a social system" (pg. 6) and innovation as "an idea, practice or object that is perceived new to an individual or other units of adoption" (pg. 11). He [9] also defines a social system as "a set of interrelated units engaged in joint problem solving to accomplish a common goal" (pg. 23). From a rural community perspective and for the purposes of this study, a social system is considered a group of people with sets of customs, behaviors and ideas intended to improve their wellbeing.

The innovation adoption process, being the interaction between society and technology, produces disruptions which are either positive

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or negative changes in adopters' daily lives or social systems. Disruption here, simply means alterations in a social system. This circumspect definition is used as disruptiveness spans across what is being disrupted, its scope, scale, time and how it occurs [10]. Positive disruptions are accrued through the benefits of an innovation as new lifestyles enhance adopters' wellbeing and socio-economic status. Whereas negative disruptions are the changes in a social system that are perceived as sacrifices or trade-offs to realize the adoption of an innovation. In a rural SSA context, examples of positive disruptions are the use of mobile phones or a clean toilet facility, while negative social disruptions are the upfront cost in purchasing a mobile phone or using bio-slurry (i.e., liquid residue from a biogas digester) as fertilizer in farms. Assuming that all humans desire improvements in wellbeing, understanding RTech's potential to effect positive or negative changes in a user's life is essential to increasing adoption rates, especially in rural SSA where poverty is pervasive.

Users of off-grid RTech determine when, how, and what quantity of energy is produced. User energy behavior, lifestyles and social norms are critical factors influencing the effectiveness and subsequent adoption of RTech. As such, the social aspect of technological development is relevant for the sustainable transition to a low-carbon future and more importantly, in facilitating poverty alleviation in deprived rural SSA communities. Nonetheless, there is still limited knowledge of the co-evolution and mutual relationship between users and RTech, the various factors of the RTech adoption process (i.e., the technology, users or institutions) and the respective impacts of these elements on the adoption process [11,12] given that they do not function in isolation. This paper seeks to address this gap by adopting a socio-technical framework to examine how the needs and lifestyles of rural people in SSA influence the adoption and sustainability of RTech at the community level and how this in turn reshapes their social systems to further affect the adoption process.

This research reviews the current literature on RTech adoption at the community level using three attributes of innovation from the IDT - namely relative advantage, compatibility and complexity. It does this by highlighting the disruptions caused in adopters' daily lives and how they in turn influence the adoption process. Firstly, a theoretical overview of a socio-technical framework is described with emphasis on RTech adoption at the community level. It then describes the methodology used to review current literature on RTech adoption in rural SSA communities, focusing on solar PV, domestic biogas digesters and ICS. The study adopts a novel framework vis-à-vis a multi-dimensional analytical approach to investigate RTech adoption in rural SSA. In doing so, it contributes to the nascent social science scholarship in energy research by highlighting intrinsic adopter socio-technical factors necessary for decision-making.

2. Theoretical framework

A socio-technical framework (STF) emphasizes the co-evolution and mutual adaptation of society and technology [13], given that new technology adoption causes some level of societal change and social behaviors also require some level of technology adaptation (Fig. 1). This review therefore, specifically focuses on low-carbon energy transitions at the community level to reveal inherent interactions between users and RTech. Actors at this level experiment initiatives of the international community, such as the use of cleaner energy services, to address broader policy issues associated with climate change and poverty alleviation. Understanding the factors that influence RTech adoption at the community level is critical in generating positive outcomes needed to meet United Nations Sustainable Development Goals 7.2 – i.e., significantly increasing the share of renewable energy in the global energy mix by 2030. Further, greater RTech adoption increases the chances of limiting global temperature rises below the 2 °C above pre-industrial levels set by the United Nations Framework Convention on Climate Change [14].

To understand RTech adoption in SSA communities, we adopt Rogers' IDT [9] which identifies five attributes of innovation. They are: 1) relative advantage; 2) compatibility; 3) complexity; 4) trial ability; and, 5) observability. They can be defined as follows: relative advantage as "the degree to which an innovation is perceived as better than the idea it supersedes" [pg. 15]; compatibility as "the degree to which an innovation is perceived as consistent with the existing values, past experiences and needs of potential adopters" [pg. 15]; complexity as "the degree to which an innovation is perceived as difficult to understand and use" [pg. 16]; trial ability as "the degree to which an innovation may be experimented with for a limited basis"; and, observability as "the degree to which the results of an innovation are visible to others" [pg. 16].

These IDT attributes allow an understanding of how disruptive innovations change social systems and how these changes in turn influence their adoption. Furthermore, adopting IDT is crucial because the transition to low-carbon technologies in rural SSA is generally through a top-down governmental approach, being mostly donor-funded projects importing system components from nations outside of SSA. Hence, RTech in rural SSA must be designed to adapt to the specific social systems of potential adopters. In this way, applying the innovation attributes facilitates a more critical examination of how the different embedded software components of RTech might influence adoption. This is in contrast to theories of predictive behavior which are also used in the literature to examine innovation adoption, such as theory of planned behavior, social cognitive theory, theory of rational action and unified theory of acceptance and use of technology [15,16]. These theories focus on the socio-psychological factors (on the user side) responsible for innovation adoption, placing less emphasis on the attributes of the technology itself. However, as there is limited literature discussing these factors in the SSA context, we focus mainly on attributes of RTech. This was an important element of this study as the technologies under investigation are usually imported into the communities where they are used, hence the need to examine their socio-technical appropriateness.

Key *technical challenges* to the adoption of RTech in SSA arise from the absence of adequately skilled and well-informed personnel for RTech design, installation, maintenance and policymaking [17,18], despite significant efforts to roll-out RTech, such as Pico PV and solar home systems (SHS), that are affordable for both rural and urban dwellers [19–22]. Indeed, a lack of skilled personnel to design and maintain biogas technologies hampers both adoption and retention rates. Further, once funding dries up, many donor-funded biogas projects often fall into disrepair due to lack of spare parts and skilled technicians [23].

The *socio-cultural challenges* of RTech adoption often relate to social structures, norms, awareness, perception of risk and lifestyle issues [24], and education [25–27]. Low education amongst most rural dwellers in SSA is likely to lead to both a lack of awareness and understanding of RTech as well as limited skilled labor needed to champion the renewable energy agenda of a community. Hence, the cultural-appropriateness of RTech in disenfranchised societies is of particular relevance in enhancing adoption and sustainability. Examining the RTech adoption decision process in communities where there is limited understanding of its benefits and adequate skills for its operation and maintenance will help uncover the underlying factors influencing adoption. The remainder of the manuscript investigates RTech adoption in rural SSA communities using three attributes of innovation – relative advantage, compatibility and complexity.

3. Materials and methods

This review focused on ICS, solar PV and domestic biogas digesters, being among the five most distributed RTech (together with wind and hydropower) in SSA [28]. These technologies were chosen to examine the socio-technical determinants of RTech adoption at the household

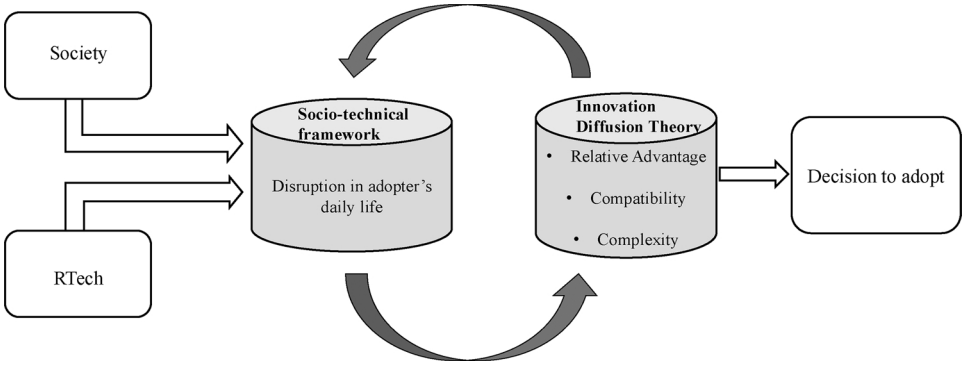

Fig. 1. Scheme of the socio-technical theoretical framework using Rogers' Innovation Diffusion Theory to examine RTech adoption (by authors).

level, given the substantial literature available documenting the impacts of their adoption. Keywords used for the search were grouped into RTech types (1. Improved biomass cooking stove; 2. Clean cooking stove; 3. Solar PV; 4. Pico PV; 5. Solar lantern; and, 6. Biogas digesters), 42 countries in SSA[1] and core terms relevant to the topic (1. Adoption; 2. Challenges; 3. Diffusion; 4. Dissemination; 5. Energy; 6. Rural; and, 7. Sustainable). All identified abstracts of articles were examined and narrowed down to those that focused on RTech adoption at the community level in terms of: 1) technology design; 2) energy-use behavior; and, 3) socio-cultural acceptance. Due to the limited publications on socio-technical renewable energy systems in SSA, articles covering the socio-economic aspects of RTech adoption were also analyzed. These articles provided further insights into the social aspects under consideration. A total of 31 documents (peer-reviewed articles and a report) matching these criteria were analyzed. Data gathered was from 15 SSA countries. Main frameworks identified were socio-economic, economic and technical, representing 32.2 per cent, 19.3 per cent and 16.1 per cent respectively. 48.3 per cent of the studies were quantitative, 29 per cent qualitative and 22.5 per cent used both methods. Two studies used IDT as a theoretical framework and one adopted a socio-technical approach (see Appendix A Table A1 for a full description of documents). Insufficient data in the initially planned ten-year study period of 2007 to 2017 was expanded to include articles from 2003 to 2018. This review is therefore based on all data available through a google scholar search for the time period of the study, as well as for what was relevant for the technologies and region being examined. The University of Western Australia online library, Onesearch, was used, having access to 9552 academic journals across a wide range of disciplines. A total of 23 papers were downloaded from Science Direct, two from Molecular Diversity Preservation International and Multidisciplinary Digital Publishing Institute and remaining from Springer, Emerald Insight, Cambridge Core, Mason Publishing and Sage journals.

The attributes of relative advantage, compatibility and complexity were deemed most appropriate in a socio-technical analysis related to technology design, energy-use behavior and socio-cultural acceptance. Also, as suggested by Rogers [8] and other studies on diffusion of innovation [29,30], these three attributes are more influential in adoption decision-making than the latter two. Socio-economic factors such as income generation, improvement of user's wellbeing and status are discussed under relative advantage. These are classified into the three key benefits of RTech identified in the documents analyzed: time savings, income savings and reduced indoor air pollution (IAP). Also, factors influencing the appropriateness of RTech in a user's way of life are discussed under compatibility – i.e., compatibility with values, past experiences and needs of potential adopters.

Finally, factors that suggest RTech adopters are unable to operate, maintain and realize the associated benefits are discussed under complexity. Studies reviewed had identified factors influencing or impeding RTech adoption as per attribute definitions in Section 2.

Factors influencing the relative advantage (Fig. 2) and compatibility (Fig. 3) of RTech were found in more than half of the documents analyzed (54.8 per cent and 58 per cent, respectively). Those related to complexity (Fig. 4) were discovered in only eight documents (25.8 per cent). Any combination of two of the three attributes were identified in five documents, while all three were in only three documents. A total of 19 documents discussed only one attribute of innovation.

4. Types of RTech adopted in SSA

This section provides an overview of the adoption of the three technologies relevant to this study: ICS, solar PV and biogas digesters.

4.1. Improved cook stoves

ICS consist of locally-designed stoves made of clay, mud or dried grasses (Fig. 5b) and manufactured stoves (Fig. 5a, c–f) designed in either local or international factories [31]. The main benefits of ICS are fuel efficiency, reduced cooking time and less IAP. Depending on the ICS design, other benefits may include income savings on the purchase of firewood and kerosene, time savings from firewood collection, poverty alleviation, health improvement, a decrease in deforestation and reduced GHGs. Hence, ICS are categorized into simple stove technologies with minimal combustion efficiencies (e.g. Upesi Jiko), intermediate stove technologies with improved combustion chambers (e.g. Stovetec, Envirofit and Advent stove) and advanced biomass stoves with forced ventilation (e.g. updraft gasifier cooker) [32]. Estimates suggest that one in six SSA households has transitioned from cooking with the traditional three-stone stove to a clean cooking technology (*i.e.*, biogas, solar and liquid biofuels). The penetration rate of intermediate ICS doubled from four million in 2011 to eight million in 2013 [35]. In early 2014, the penetration of advanced biomass ICS was in its early stages with between 40,000 and 100,000 draft gasifiers distributed in pilot projects. The lack of reliable data on the penetration of simple or low-end ICS could be attributed to the fact that they are usually manufactured by individuals for personal use, with no accessible records. In January 2013, the Government of Malawi announced a national distribution target of two million clean and efficient cook stoves by 2020 [36]. If successful, this program will induce half of all Malawian households to adopt ICS by 2020 – an estimated four million households – a dramatic shift from the over 90 per cent of households currently burning solid fuels using traditional three-stone stoves.

[1] The countries in SSA are: Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Central African Republic, Chad, Democratic Republic of Congo, Republic of Congo, Cote d'Ivoire, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Gambia, Guinea, Guinea Bissau, Kenya, Lesotho, Liberia, Malawi, Mali, Mauritania, Mozambique, Namibia, Niger, Nigeria, Rwanda, Senegal, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, Tanzania, Togo, Uganda, Zambia and Zimbabwe.

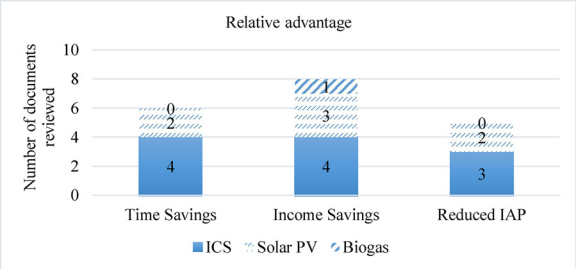

Fig. 2. Distribution of documents discussing RTech relative advantage.

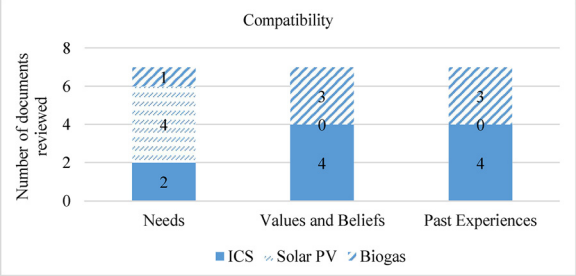

Fig. 3. Distribution of documents discussing RTech compatibility.

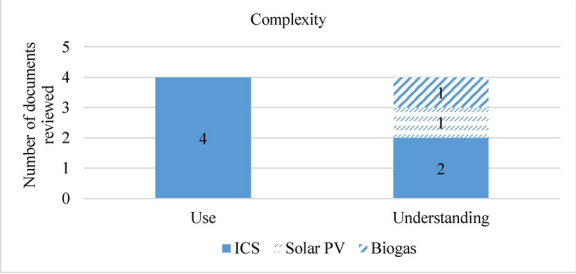

Fig. 4. Distribution of documents discussing RTech complexity.

4.2. Solar PV

SSA is one of the sunniest places in the world with an unevenly distributed solar energy resource ranging from $4 \times 10^{-3} - 7 \times 10^{-3}$ MWh/m^2 (megawatt hours per square meters) [37]. The technical potential for solar PV is as high as 6.567×10^9 MWh [38]. The entire region has the potential to meet its daily domestic load requirement of 2.324×10^{-3} MWh/m^2 [37]. Solar PV includes SHS, off-grid solar arrays and Pico PV systems such as solar lanterns (Fig. 6). SHS and Pico PV systems in rural SSA are primarily used for lighting, charging of mobile phones, watching television and sometimes for refrigeration [39,40]. In Kenya, more than 320,000 SHS were installed by the end of 2010 [19]; the installed capacity rose to 16 MW (MW) by 2012 and 20 MW by November 2013. In Ghana, 9536 SHS were installed in over 70 districts of rural communities through funding from the World Bank, Japan International Cooperation Agency and the Spanish Government [20]. Further, the Spanish government funded the installation of more than 1300 SHS in public institutions in Ghana. As a result, the solar industry in Ghana has grown steadily, with a total of 64 registered companies by the end of 2013. The sale of Pico PV systems in SSA was estimated to have increased from less than 100,000 in 2010 to over four million in 2014, with two-thirds of this in East Africa, specifically Kenya, Ethiopia and Tanzania [41]. With the right policies and continued cost reduction, solar PV could play a major role in SSA's energy supply [42].

4.3. Biogas digesters

Biogas digesters are used to anaerobically decompose biodegradable materials such as kitchen waste, human and animal excreta to produce biogas (comprising of methane, carbon dioxide, and small traces of hydrogen sulphide) and bio-slurry [45]. Biogas has a fuel efficiency of 35 per cent and can be used for cooking, lighting and electricity generation [46]. The nutrient-rich bio-slurry is used as fertilizer for crop production. Most biogas digesters installed in SSA are household (Fig. 7), institutional or community, or large-scale units [47]. Household units are usually fed with animal, human or kitchen waste, producing enough gas for all cooking needs and about two to four hours of lighting for a family of eight. Institutional or community units are typically used in schools, hospitals or public latrines and also use human and animal waste as feedstock. Large-scale biogas units rely on large amounts of human and agricultural waste, with the gas often used to generate electricity and the slurry to produce fertilizer. Biogas digesters were introduced in Kenya and South Africa as early as the 1950s [47]. In Rwanda, an initiative by the Food and Agriculture Organization (FAO), saw the construction of four biogas digesters (ranging from 8 to 20 m^3) by a Nepalese consultant in 1982 [23]. In Tanzania, biogas digester dissemination commenced in 1975 with the construction of 120 floating drum plants in Arusha. From the 1950s to date, various international organizations (such as the Netherlands Development Organization, the Netherlands Directorate General International Cooperation, the German Technical Cooperation and Winrock International) have installed numerous biogas digesters across Burundi, Botswana, Burkina Faso, Côte d'Ivoire, Ethiopia, Ghana, Guinea, Lesotho, Namibia, Nigeria, Rwanda, Zimbabwe, South Africa and Uganda [52,53]. Biogas technology has however, received little attention in recent times primarily due to high construction costs, little technological advancement, lack of reliable feedstock and limited mobility, amongst others [48,54].

5. Socio-technical factors influencing RTech in SSA

This section discusses RTech adoption from a socio-technical perspective using relative advantage, compatibility and complexity as units of analysis from the publications matching the selection criteria.

5.1. Relative advantage

RTech are promoted in SSA for their capacity to provide affordable energy, reduce fuel consumption, IAP, cooking and firewood collection times. Fig. 8 shows that affordability plays a major role in the adoption of all RTech. Fuel purchase is a factor influencing both ICS and solar PV adoption. Other RTech relative advantages - such as short cooking time, reduced IAP and provision of light - were not found to affect biogas adoption. The remainder of this section discusses RTech relative advantage under time savings, income savings and reduced IAP.

5.1.1. Time savings

Across the adopter spectrum, fast and slow modern energy technology adopters desire improvement in their wellbeing. This translates into the uptake of RTech being influenced by a range of advantages and disadvantages as understood by the user. Time savings can potentially reshape individual daily lives over time, and eventually the entire society if critical adopter mass is reached. RTech adoption due to time savings shows that adopters are willing to reshape their social systems to enhance wellbeing. For instance, in rural Ethiopian communities where only 1 per cent of inhabitants had time for social and leisure activities, time saving from cooking and firewood collection would be valuable [55].

During ICS adoption, reduction in cooking time is crucial. Cooking

Fig. 5. (a) Three-stone stove [33]; (b) Upesi Jiko [34]; (c) Advent stove [33]; (d) Stovetec [33]; (e) Ugastove [33]; (f) Envirofit [33].

is an ongoing, life-central activity performed about two to three times a day; hence, changes in the time it takes will have significant impacts on a community. ICS are designed differently from the traditional three-stone stove, often requiring some getting-used-to in terms of igniting, fire attendance and cooking mode (i.e., standing or sitting). During this period, the evaluation of cooking time is critical to understanding how an ICS will alter the structure of user social systems. Changes in cooking time can be evaluated immediately after the cooking process, providing a simple means to assess the social impacts of ICS adoption. Fire attendance and cooking mode, on the other hand, are characteristics that are limited to the user and the technology, hence do not have the potential to disrupt the broader social systems. Investigating ICS adoption in Uganda, survey respondents preferred the Stovetec to Ugastove due to its shorter cooking time, despite a lower fuel efficiency (38 per cent) than Ugastove (46 per cent) [33]. It is, however, interesting to note that Adkins et al. [33] found the Stovetec to be 4 per cent slower than the three-stone stove.

Time savings in firewood collection, an activity usually performed by women, is another factor influencing ICS adoption [56]. In Malawi, a study revealed that the Chitetezo Mbaula reported a 50 per cent reduction in fuel consumption leading to a 44 per cent decline in how many times firewood is collected [57]. This generated savings of six to eight hours in firewood collection per month. Kees and Feldmann [58] also reported that an ICS saves a family 3.1 kg of firewood and seven hours per week on cooking and firewood collection activities. Unlike savings in cooking time, time savings due to reduced firewood consumption cannot be evaluated immediately by ICS adopters. That is, when the average household spends approximately two hours on firewood collection a day [35], 30 min saved in cooking can, for instance, be used to attend an evening church service. This will have a positive influence on ICS adoption compared to the knowledge of a six to eight hours per monthly savings on firewood collection. Given the scarcity of research investigating ICS performance in real world conditions, it is unknown whether rural households adopt ICS due to time savings in cooking or firewood collection.

Investigating solar PV adoption by Müggenburg et al. [22], 78 per cent of users stated that household chores can be performed more easily, with 50 per cent of adopters citing greater flexibility in time management and a more spontaneous lifestyle due to the increase in light hours at night. A total of 11per cent attributed the ease of doing household chores to the decreased travel of long distances to buy fuel or charge mobile phones. In some remote rural SSA communities, charging a mobile phone at the nearest grid-connected shop could take almost half a day [59]. In these communities, the convenience of SHS users

Fig. 6. Solar PV applications in rural SSA: (a) SHS installed in rural Senegal [43]; (b) Pico PV systems in Ethiopia [22]; (c) Off-grid solar PV system in Kenya [44].

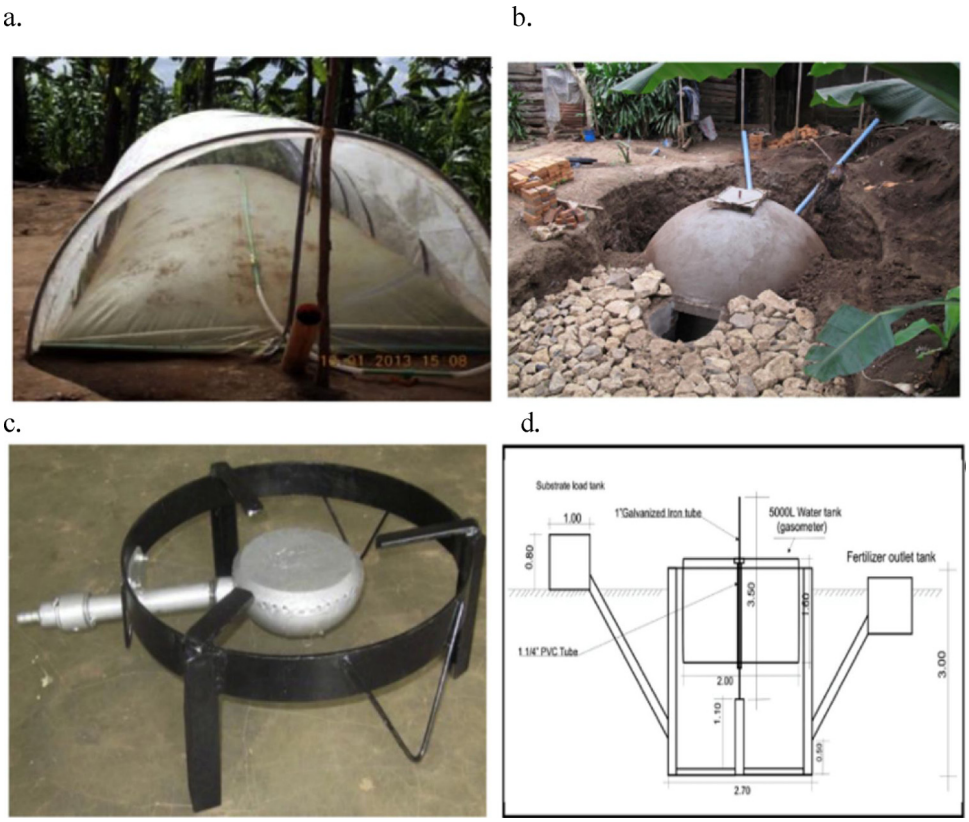

Fig. 7. (a) Flexi biogas system installed in Kenya [48]; (b) Fixed-dome biogas digester in Arusha, Tanzania [49]; (c) Biogas stove [50]; (d) Lay-out of an installed biogas digester [51].

charging their mobile phones in their homes surpasses other benefits of the system.

Furthermore, no studies were found reporting time savings influencing biogas adoption. Biogas digesters could however, provide significant time savings as the switch from a three-stone stove to a biogas burner eliminates the time, energy and money spent on the collection or purchase of firewood. These changes can be easily evaluated compared with the seasonal use of bio-slurry as fertilizer. The biogas cooking experience could, therefore, trigger the most profound change in adopters' daily lives because it provides a faster cooking process due to its higher specific energy content compared to firewood [46,60]. A total of six studies identified that user preference for shorter cooking time of ICS, biogas burners or the three-stone stove is key to adoption decision-making.

5.1.2. *Income savings*

A significant factor influencing RTech adoption in SSA is income savings vis-à-vis reduced firewood consumption, which can be

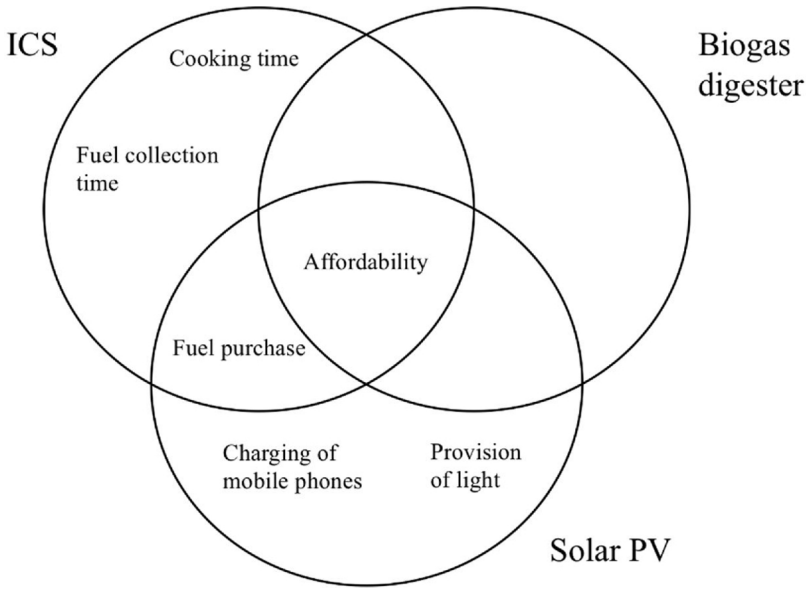

Fig. 8. Venn diagram for ICS, biogas digester and solar PV's relative advantage in SSA.

redirected to other expenditure for business, education, or other good improving the economic and social status of household members. The knowledge of this savings and the ability to purchase alternative goods or services is likely to influence adopters' decision in RTech adoption.

The relatively high fuel efficiencies of most ICS mean that less firewood is required for cooking, which in turn leads to a reduction in firewood expenditures. The rocket mud stove was reported to reduce fuel consumption by 34 per cent compared to the three-stone stove [61]. Also, adopters of the Roumdé, an ICS disseminated in Burkina Faso, reported using 20 per cent to 28 percent less wood fuel compared to the three-stone stove [62]. Another study in Ethiopia reported that switching from a three-stone stove to an ICS reduced firewood consumption by 20 per cent to 56 per cent [63]. Kees and Feldmann [58] estimated that fuel saving from ICS adoption was around 27 Euro per year in firewood cost. User ability to appreciate cost savings and the associated positive disruptions on their socio-economic status is a crucial part of RTech adoption. Some rural dwellers however, purchase charcoal during the rainy season [56,64] and do not necessarily buy firewood throughout the year. Others have access to free firewood therefore, ICS adoption does not impact household activities in terms of budget [56].

Furthermore, solar PV adoption in rural Kenya and Malawi was reported to reduce expenditure on kerosene costs and mobile phone charging [65,66]. In Central East Africa, annual savings of $46.8USD were reported [29]. Adopters of biogas digesters in rural Uganda however, did not appreciate the money savings of biogas technology as they had access to a no-cost supply of firewood and attached little or no value to collection times [67].

Affordability remains a significant challenge impeding RTech adoption in SSA. RTech acquisition and installation costs are often beyond the purchasing power of most rural dwellers and need long term planning and savings, especially when the money saved could be alternatively used for other needs such as payment of school fees, hospital bills or as seed money for business ventures [7,62]. Making a one-time payment for the purchase of RTech continues to challenge the majority of poor, rural population given their constrained ability or lack of experience with long-run savings or return-on-investments realized via RTech adoption. Household decision-making is often issue specific and gender related [68], highlighting different motivations for RTech acquisition. Usually the women or wives, who are responsible for cooking, often with limited financial resources, are the decision makers during ICS adoption. They are also more concerned with firewood collection times, cooking time and IAP. In contrast, the men or the husbands are likely to adopt an ICS or SHS for prestige [56,59]. This highlights the importance of adopter perceptions regarding RTech relative advantage, with adoption likely to be higher if there is an understanding and appreciation for immediate disruptions and subsequent lifestyle impacts. Since the majority of subsistence farmers and other rural populations tend to live on a day-by-day basis, information such as daily savings may well be relevant to their daily decision-making in the context of relative scarcity and in turn the adoption decision process. For instance, knowledge of household lighting or quality of meal, due to income savings, are relevant information likely to facilitate RTech adoption. In contrast, detailed understandings of monthly or yearly savings and investment planning may require a new value system which would take a longer time to adopt, thereby hindering the adoption decision process.

5.1.3. Indoor air pollution

Another well-known attribute of RTech is its capacity to reduce smoke emissions, with the key question being whether this motivates rural dwellers to adopt RTech.

ICS are often touted as better alternatives to the three-stone stove because they produce less smoke emissions. Interestingly, in rural Kenya, households with little food were least affected by IAP and would prioritize food security over the purchase of an ICS [7]. In households where food security was a lower priority, the solution to IAP was to build an outdoor kitchen. Martin et al. [69] found respondents appreciative of the immediate benefits of reduced smoke emissions and risk to burns when using the top-lit updraft gasifier stove. Long-term health benefits, on the other hand, were not valued and not considered important factors influencing adoption decisions. Women responsible for cooking in rural Senegalese households also reported a 9 per cent decline in respiratory symptoms and eye problems [70]. This was however, found in a self-reported health study that did not use objective indicators such as individual particulate matter exposure.

As with time and income savings from reduced firewood consumption, the health benefits from reduced IAP do not generate immediate daily life changes nor have a greater influence in the adoption decision process. In poorer households, fuel savings may be more valued as it translates into cost savings. The studies reviewed were found assessing ICS's ability to reduce IAP without showing how it encourages adoption. Such information will confirm laboratory tests results and further enhance ICS dissemination strategies and adoption. Since the health benefits of reduced IAP require a longer time to be realized, ICS can be classified as preventive innovations associated with a low adoption rate.

Using solar PV generates no smoke emissions and has the potential to significantly reduce IAP. In rural Ghana, households using SHS reported 45 per cent lesser incidence of blackened nostrils compared to households using kerosene lanterns [71]. In a village in Ethiopia, 89 per cent of survey respondents saw the adoption of Pico PV systems influenced by improvements in health and hygiene, namely, reduction of eye and nose irritation given the absence of soot from oil lamps and smoke from kerosene lanterns [22]. Some evidence also suggested a decline in insects attracted to the animal blood and hence reduced food contamination.

Cooking or lighting with biogas also do not generate smoke emissions and has the potential to reduce IAP. However, studies were not found reporting adopters' preference for biogas digesters due to this quality. The prohibitive cost of biogas digesters or relatively fewer dissemination programs could explain why other relative advantages were not found motivating their adoption. That is, few people in rural SSA have acquired biogas digesters to examine these benefits in the real world.

5.2. Compatibility

Examining RTech compatibility in a social system demonstrates how changes in adopter's daily life, technology trade-offs and competing relative advantages influence adoption. Innovations that are inconsistent with existing values and beliefs of a society require new value systems which often take longer to adopt [9]. Changes in the social structure are usually difficult to achieve and therefore, stimulated by other attributes of innovation such as relative advantage. In Fig. 9, apart from the provision of light, all factors influencing RTech compatibility in SSA are peculiar to each technology. Following Rogers [9], this section discusses RTech compatibility in terms of needs, values and beliefs and past experiences.

5.2.1. Compatibility with needs

For ICS to be desirable, their relative advantages should match the needs of potential adopters. In rural Uganda, for instance, the household primary cook, usually the wife or the eldest daughter, disliked the Ugastove because of its longer cooking time despite its higher fuel efficiency [33]. Also, when the primary cooks in rural Malawi were asked to choose between sugar and the Chitetezo Mbaula, results showed that fuel savings did not influence ICS adoption but rather the hours spent collecting firewood [36]. These insights imply that time savings may influence ICS adoption more so than fuel savings. Studies have shown that when rural dwellers have access to electricity, solar PV for that matter, their needs and energy-use behavior change [39,72], with many acquiring new appliances such as mobile phones, TVs and refrigerators.

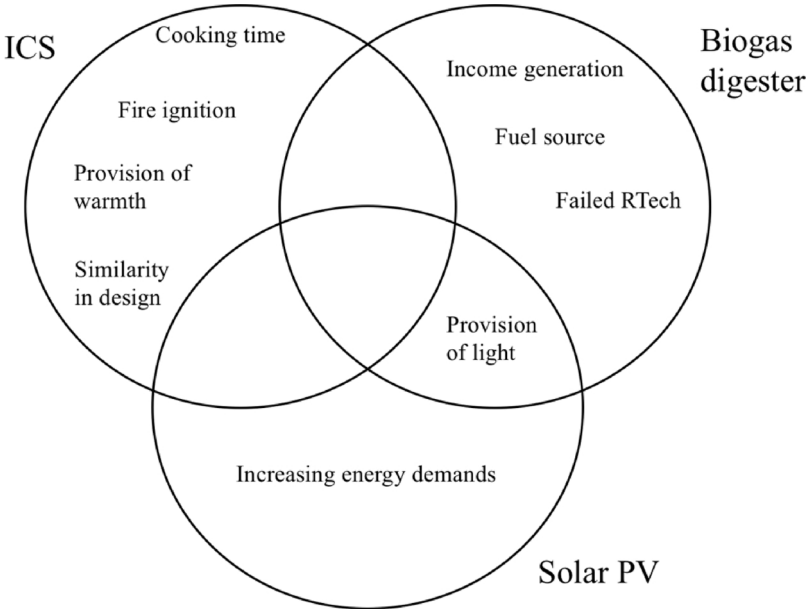

Fig. 9. Venn diagram for ICS, biogas digester and solar PV's compatibility in SSA.

Over time, their energy demands increase and become incompatible with the capabilities of RTech. As such compatibility can be described as an attribute that evolves according to an adopter's socio-economic status. After a period of time, an adopter's desire for positive lifestyle changes can affect RTech sustainability. A study investigating the battery lifespan of off-grid PV systems in rural Rwandan schools and hospitals showed that there was an increase in energy demand because access to electricity led to the acquisition of new electrical devices [39]. Increase in energy demand was responsible for battery malfunction in half of the surveyed sites of the study. A similar study in Nigeria also found that unexpected increase in energy demand resulted to decreased battery lifespans in off-grid solar PV systems [73]. Some unexpected energy-use behaviors identified in these studies were the use of TVs and refrigerators during off-peak hours and warmer seasons, respectively (also refer to [29,74]). The design of RTech, therefore, goes beyond meeting user energy needs. It also encompasses the design of systems that are adaptable to lifestyle changes in order to foster sustainable energy supply.

Furthermore, in some rural households, the significance of a biogas digester decreases when the biogas lamps stop working [75]. In these instances, biogas served as a source of lighting and firewood was still used for cooking because it was cheap, if not free, and readily available. Although cooking is essential to the livelihood of all people, some rural populations tend to place less value on the fuel required for this activity given the relative abundance of cheap firewood. To these biogas adopters, fuel cost savings are not compatible with their needs and are less likely to cause any positive lifestyle changes. Lighting, on the other hand, meets their needs due to low electricity access and the biogas lamp or solar PV provides a cleaner and cheaper source of lighting. Some households see nothing wrong with their methods of cooking [76] and would adopt a biogas digester only if it engenders income savings. Money saved from kerosene purchase could be another factor influencing the use of biogas for lighting. Unlike income savings from reduced firewood, the prospects of no longer having to buy kerosene is easy to comprehend. In other households, the higher the number of planted trees, the more likely a biogas digester would be adopted [75]. Adopting a biogas digester may also provide an opportunity to generate income as owners will no longer use their trees as firewood for cooking but rather sell them to other households. These examples illustrate that differential needs (i.e., lighting and income generation) among different socio-economic strata in one community can influence biogas adoption. It can also be argued that the need for lighting can possibly be relegated to a second level in households that have electricity connections, causing an incompatibility of needs, further decreasing the significance of a biogas digester.

5.2.2. *Compatibility with values and beliefs*

Compatibility with values and beliefs emphasizes the cultural appropriateness of a technology. That is, the extent to which the new RTech fits into the existing energy-use behaviors and lifestyles of adopters.

In Uganda, participants in a study did not value the health benefits of ICS, arguing that the long-term use of the traditional three-stone stove automatically disproved negative health implications [69]. Further, Sesan [7] found that, the prohibition of IAP in Kenya was not because of its associated health impacts, but was due to embarrassment of soot accumulated on the walls to the household head (usually the man) when visitors came over. In this study, the Upesi Jiko recorded the highest adoption rate because its design was culturally more appropriate than other smoke alleviation interventions, despite its high emissions. Education and awareness-raising would help potential adopters understand the relevance of these benefits, thereby catalyzing the adoption decision process.

Apart from cooking, the fireplace often provides social benefits [77]. For instance, in the Tswana culture in Botswana, the fireplace draws family members together in the evening. Stories are told and family issues discussed. Residents in rural Kenya apparently preferred the additional benefit of the warmth provided by the three-stone stove during the cooking process [78]. They saw a disadvantage in the inability of gasifier cooking stoves to heat space, and may well reject a biogas digester for cooking as using an ICS or the biogas burner would mean finding an alternative source of warmth for family gatherings. Although, this choice may not necessarily affect the cooking process, it can influence the rejection of an ICS or a biogas digester especially if other benefits such as fast cooking time, appropriate design or lighting are compromised and deemed less important.

A major challenge associated with biogas adoption in rural communities is the idea of using human or animal excreta as a source of energy. Residents of Kenya, Ghana and Ethiopia were reported to question the safety of the energy source, while others entirely rejected the idea mainly because of taboos or misconception about its safety [48,75,79]. Similar to long-term cost savings, characteristics of RTech that cause significant changes in an adopter's way of life impede or are less likely to encourage RTech adoption. Benefits or characteristics of RTech that require new value systems would take a longer time to be understood.

5.2.3. Compatibility with past experiences

The compatibility of RTech with past user experiences in SSA is another factor influencing the adoption process. Similar to compatibility with values and belief, users are accustomed to or adapted a particular way of using energy technologies which in turn has shaped their lives. The adoption of a different technology that requires relearning and lifestyle adjustments may be rejected. Compatibility with past experiences entails the physical interaction between adopters and technologies as well as being familiar with benefits and design similarities.

An example of incompatibility with past experiences is 60 per cent of interviewees reported the Ugastove and Advent stove were too tall for the cooking task [33], having a different height from the usually low-lying three-stone stove at which users sat during cooking. On the other hand, 90 per cent of the respondents in Tanzania preferred the Stovetec and Envirofit for their design and compatibility with most cooking tasks. Also, in rural Burkina Faso and Cameroon, women were more inclined to adopt ICS similar to the three-stone stove and suited local cooking habits [56,62].

In an isolated case, the health benefits of reduced IAP played a major role in the uptake of the Upesi Jiko in households that already adopted water treatment equipment [80]. Silk et al. explained that "treating water more frequently is consistent with the hypothesis that health messages and corresponding product intervention reinforce one another" [80]. These examples show that ICS with known benefits, similar designs and cause little disruptions are likely to have higher adoption rates.

Similarly, past experiences with RTech also influence the decision to adopt similar technologies in the future. Negative attitudes towards innovation is a significant obstacle to biogas adoption in SSA [48,54,81] with bad perceptions of failed biogas projects tending to discourage the adoption of new biogas digesters. Sovacool et al. [48] found that experiences with failed biogas projects deterred the use of flexi biogas systems despite the value users placed on their ability to uninstall and move the biogas digester to other locations. When rural dwellers, considering their limited resources, invest money into an RTech and do not see an improvement in their socio-economic status, it becomes difficult to adopt technologies with similar characteristics and benefits.

5.3. Complexity

The ability to use a technology with ease is the third and last integral part of the adoption decision process discussed in this paper. When a technology functions similar as its predecessor, it has a higher probability of adoption than when it requires relearning [9]. From Fig. 10, main complexity challenges identified were awareness of RTech and understanding how the systems operate.

5.3.1. Complex to use

ICS are designed to be thermally efficient for specific fuel types, usually for firewood or charcoal [64]. When an ICS is designed for only firewood, it cannot be used during the rainy season, leading to a possible rejection or undermining the adoption of another ICS in future. In households where fuel is collected, fuel type determines appropriate stove technology. The three-stone stove, for instance, is flexible in terms of the size and type of biomass fuels. In Tanzania, households were found allocating different fuels for different purposes: preparing chapatti, simmering beans, quick heating of tea, indoor heating and/or heating of bathing water [64]. Designing an ICS that embodies a wide-range of benefits has led to the design and manufacture of ICS that prioritize some benefits at the expense of others. An ICS with similar designs as the three-stone stove does not require relearning and can use multiple fuelwood, thereby causing less negative disruptions and be more likely adopted faster. In Uganda, the Ugastove, for instance, was reported to be tall, bulky and heavy, and made cooking difficult [33]. It also had a metal shell that heated up and was inconvenient during cooking. In addition, a greater amount of fire-tending required by the Ugastove interfered with other activities such as child care. The top-lit updraft gasifier stove was also reported to be difficult to light and slowed the cooking process [69]. Furthermore, in Tanzania, the Advent stove was rejected because it was too small [33]. ICS adopters in these studies tend to measure the complexity of the technology based on their past experiences with the three-stone stove. As discussed in Rogers [9], complexity as an attribute of ICS adoption is very similar to compatibility with past experiences. This could explain studies where it was found that adopters decided to revert to the three-stone stove after trialing an ICS for a few months [82].

5.3.2. Complex to understand

Another dimension of complexity is adopters' ability to understand how a technology works and grasp the relevance of its benefits. That is, how an RTech will alter daily lifestyles to improve user wellbeing is integral to the adoption decision process and proper use of a particular technology. Rogers [9] explained that this aspect of complexity is similar to the compatibility with values and beliefs, as a new value system is required for adopters to comprehend the potential benefits of a technology. As discussed under compatibility with values and beliefs, ICS adopters in [7,82] required a new value system facilitated by education and awareness-raising in order to comprehend the long-term health benefits of reduced IAP.

In one study, the lack of technical knowledge of the operation of solar PV was attributed to abuse of systems as users did not understand why charging their phones during the day resulted in having little energy to switch on lights at night [29]. Rural dwellers' inability to understand such technicalities also accounts for changing energy-use behaviors that do not meet system requirements resulting into system failures as discussed earlier under compatibility with needs.

Furthermore, biogas adoption rates in northern Ethiopia increased by a factor of 3.01 as the education level of the head of household increased by one year [75]. In this area, some residents were not adopting a biogas digester simply because they did not know that the technology existed. While it is unreasonable to assume each user grasps the science behind the operation of RTech and the correlation with reduced IAP, findings suggested that adoption was related to greater understanding of the health benefits when adoption decisions were being made. No study was found which reported on the inability of users to comprehend solar PV systems' core benefits of provision of light compared to IAP, nor their comparative cost savings with biogas and ICS adoption. This further justifies why some adopters would prefer the light component of a biogas digester.

6. Conclusion

This paper reviewed the socio-technical factors influencing the adoption of ICS, solar PV and biogas digesters in SSA vis-a-vis three attributes of innovation from Rogers' Innovation Diffusion Theory (IDT): relative advantage, compatibility and complexity. This approach facilitated the examination of the underlying factors affecting RTech adoption at the community level. The study revealed that RTech adoption in SSA is influenced by relative advantages that can be measured immediately and can possibly alter the broader social system. It also demonstrated that understanding what motivates individuals to value some benefits over others is critical in facilitating positive disruptions, thereby increasing adoption rates. For instance, the gendered division of labor in the household dictates the value users place on the various RTech benefits. These differences, however, can potentially undermine the benefits of reduced IAP as the male head of household tends to make most household financial decisions, but are usually not responsible for cooking and are less exposed to IAP. Addressing such knowledge gaps in household energy decisions-making will enhance effective RTech dissemination strategies and financing so high upfront costs will not overwhelm the importance of long-term health benefits from reduced IAP.

This review reveals that the day-by-day living of most rural populations is a factor impeding the realization of long-term RTech benefits, such as income savings from fuelwood purchase. Savings in cooking time and income savings from less kerosene purchase after solar PV

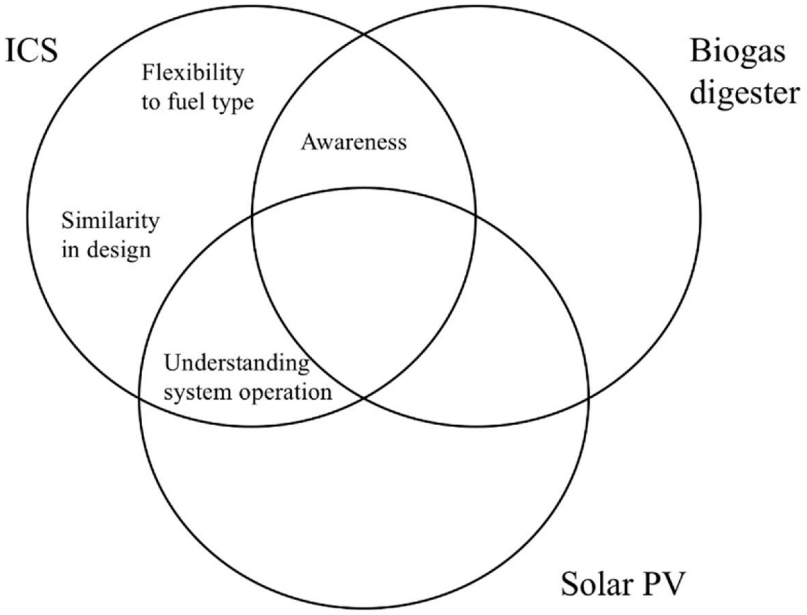

Fig. 10. Venn diagram for ICS, biogas digester and solar PV's complexity in SSA.

adoption were found to be the main factors influencing adoption. As discussed, income generation has also become a significant benefit of RTech adoption in SSA. Mobile phone charging, barbershops and the sale of cold water are currently very common businesses found in solar-electrified rural communities in SSA [83], similarly in remote communities in India, Nepal and Bangladesh [84,85]. However, our findings did not reveal whether RTech income generation activities encourage adoption as lighting and mobile phone charging do or only sustain RTech usage after adoption. Identifying the income generation capabilities of RTech, especially ICS and biogas, will be instrumental in dissemination strategies to increase adoption rates. The short-term benefits of RTech were identified as compatible with the needs and value systems of rural populations, in accordance with an improvement in their wellbeing. We also found that long-term benefits become significant when RTech have familiar relative advantages. We suggest that, with increasing living standards, preventive innovations with familiar relative advantages and designs that cause little disruptions, yet embody all core benefits, are likely to have higher adoption rates. Such a shift will promote new value systems needed to facilitate the adoption of technologies with similar characteristics and benefits. In other cases, increasing living standards come with increasing demand for certain goods, as seen with the adoption of solar PV. Compatibility is therefore not static, but changes with adopters' socio-economic status especially when the relative advantages are highly valued. Critical analysis of societal value systems will inform the development of innovations that will not fail or be rejected when the adopter's demands grow. Rogers' IDT was unable to account for these changes in an adopter's value system and how they affect innovation compatibility.

In terms of compatibility with values and beliefs, past experiences and complexity, 51.6 per cent of studies reviewed revealed that if an RTech causes less disruption it is adopted faster. For instance, apart from increasing energy demand, rural populations do not find solar adoption to be incompatible nor complex to use. This may be due to fewer interactions with users and energy production, the immediate illumination of households which is consistent with their daily lives and the absence of kerosene purchase. ICS and biogas digesters, on the other hand, require users to collect and feed systems with fuel and are associated with long-term fuel and income savings. Similarly, the knowledge that lighting is highly valued among the rural poor can be used to encourage biogas adoption in communities where human and animal excreta are deemed unsafe for energy production. RTech adoption in rural SSA however, still requires significant education and awareness-raising to improve adopters' understanding of long-term health benefits from reduced IAP and firewood cost savings. The examination of socio-technical challenges at the community level revealed that biogas adoption has substantial compatibility and complexity challenges without any distinctive relative advantage that users readily identify or prioritize. This confirms the claim made by Arthur et al. [79] that biogas adoption is the lowest among all RTech disseminated in SSA. In contrast, solar has more relative advantages that are highly valued by users and causes the least disruption.

Finally, the systematic methodology used in this paper revealed that most studies (61.3 per cent) on RTech adoption in SSA examined only one attribute of innovation. Studies with such limitations do little to foster holistic approaches to addressing the barriers to RTech adoption in SSA, especially at the household level. Investigating RTech adoption using two or all attributes of innovation is more appropriate in research aiming to understand the benefits of RTech to adopter lifestyles. Furthermore, the findings of this review shed light on the relevance of adopters in low-carbon transition decision-making. That is, in the same community, different factors influence RTech adoption according to socio-economics status, hence blanket solutions or dissemination strategies are inappropriate. This is particularly relevant when majority of these projects (51.6 per cent in this review) are funded and implemented by transnational bodies. Considering the relevance and interconnection of all innovation attributes in the adoption decision process, future research must look to adopt multi-dimensional approaches to investigating RTech adoption in SSA communities.

Acknowledgements

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Appendix A

Table A1
Description of documents reviewed.

Reference articles	Journals	Databases	Study areas	Number of citations	Lead institutions	Theoretical frameworks	RTech	Dissemination programs	Number of RTech disseminated	Document type	Year of publ.	Innovation attribute identified
Müggenburg et al. [22]	Energy for Sustainable Development	Science Direct	Ethiopia, Nazareth	22	University of Saarland, Saarbrücken, Germany	Unified Theory of Acceptance and Use of Technology[Q1]	Solar Pico PV	Disseminated by authors	Not specified (24[sz])	Peer-reviewed	2012	Relative Advantage
Wambuguh [59]	International Journal of Renewable Energy Development	Mason Publishing	Kenya, Wiyumiririe, Laikipia district	N/A	California State University, U.S.A.	Economics[B]	Solar PV	Private market-based unsubsidized project[P]	Not specified (129[sz])	Peer-reviewed	2013	Relative Advantage
Adkins et al. [33]	Energy for Sustainable Development	Science Direct	Uganda, Ruhiira, Isingiro district; Tanzania, Mbola, Uyui district	47	Columbia University, U.S.A.	Socio-economic and Technical[Qn]	ICS	Millennium Villages Project, UNDP[D]	Not specified (300[sz])	Peer-reviewed	2010	Relative Advantage, Compatibility, Complexity
Muneer and Mohamed [68]	Science of the Total Environment	Science Direct	Sudan, Omdurman	54	King Saud University Saudi Arabia, Saudi Arabia	Socio-economic[B]	ICS	Energy research council, CARE International, Sudan and other public and private research and aid organizations projects[ND]	Not specified (300[sz])	Peer-reviewed	2003	Relative Advantage, Compatibility,
Malinski [57]	Deutshe Gesellchaft für Internationale Zusammenarbeit (GTZ) report	GTZ	Malawi, Mulanje, Ntcheu and Thyolo districts	N/A	GTZ, Germany	Socio-economic[B]	ICS	Program for Basic Energy and Conservation in Southern Africa Improved Firewood Stoves Project, GTZ[D]	Not specified (327[sz])	Report	2008	Relative Advantage
Kees and Feldmann [58]	Energy Policy	Science Direct	Uganda, Bushenyi district	20	GTZ, Germany	Policy[Q1]	ICS	Ugandan Energy Saving Stove Project, GTZ[D]	Over 500,000 in 2005 (national)	Peer-reviewed	2011	Relative Advantage
Ochieng et al. [61]	Biomass and Bioenergy	Science Direct	Kenya, Siaya district	10	London School of Hygiene and Tropical Medicine, U.K.	Technical[Qn]	ICS	Promotion of Private Sector Development in Agriculture Stove Project, GTZ[D]	Not specified	Peer-reviewed	2013	Relative Advantage
Bensch et al. [62]	Journal of Economic Behavior & Organization	Science Direct	Burkina Faso, Ouagadougou and Bobo-Dioulasso	12	Rheinisch-Westfälisches Institut für Wirtschaftsforschung, Essen, Germany	Economics[B]	ICS	Dissemination program by government of Burkina Faso and GIZ.[D]	1473 (study area)	Peer-reviewed	2015	Relative Advantage
Duguma et al. [63]	Energy for Sustainable Development	Science Direct	Ethiopia, Menagesha Suba state	5	ASB Partnership for the Tropical Forest Margins, Kenya	Environmental[B]	ICS	Not specified	Not specified	Peer-reviewed	2014	Relative Advantage
Kåre et al. [64]	Sustainable Energy Technologies and Assessments	Science Direct	Tanzania, Siha district, Kilimanjaro region	6	Norwegian University of Life Sciences, Norway	Technical[Qn]	ICS	Tanzania Traditional Energy and Development Organisation Improved Stove Program[N]	Not specified	Peer-reviewed	2016	Relative Advantage, Complexity

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Table A1 (*continued*)

Reference articles	Journals	Databases	Study areas	Number of citations	Lead institutions	Theoretical frameworks	RTech	Dissemination programs	Number of RTech disseminated	Document type	Year of publ.	Innovation attribute identified
Vitali and Vaccari [56]	Sustainability	Molecular Diversity Preservation International and Digital Publishing Institute	Chad, Bongor; Cameroon, Yagoua	17	University of Brescia, Italy	Socio-economic^{Qn}	ICS	International Development Cooperation project^{D}	Not specified (161^{sz})	Peer-reviewed	2014	Relative Advantage
Walekhwa et al. [67]	Biomass and Bioenergy	Science Direct	Uganda, Luwero, Nakaseke and Nakasongola in Central Uganda, and Mbale, Sironko, Manafwa in Eastern Uganda	10	Makerere University, Uganda	Economics^{Qn}	Biogas	Variety of NGO projects^{D}	Not specified (100^{sz})	Peer-reviewed	2014	Relative Advantage
Sesan [7]	Energy Policy	Science Direct	Kenya, West Kochieng	19	Independent researcher, Nigeria	Techno-economic and Cultural^{Ql}	ICS	Practical Action's Improved stove programme^{D}	Not specified (24^{sz})	Peer-reviewed	2012	Relative Advantage, Compatibility, Complexity
Akolgo et al. [76]	Renewable and sustainable energy reviews	Science Direct	Ghana, selected 20 communities across all 10 regions	0	University of Energy and Natural Resources, Ghana	Socio-economic^{Qn}	ICS	Not specified	Not specified (500^{sz})	Peer-reviewed	2018	Relative Advantage, Compatibility,
Martin et al. [69]	International Journal of Environmental Research and Public Health	Molecular Diversity Preservation International and Digital Publishing Institute	Uganda, Sabagabo and Kira sub-counties	2	PATH, U.S.A.	Opportunity, ability, and motivation behavior change^{Ql}	ICS	N/A	N/A	Peer-reviewed	2013	Relative Advantage, Compatibility, Complexity
Bensch and Peters [70]	Journal of Health economics	Science Direct	Senegal, selected 12 villages	12	Rheinisch-Westfälisches Institut für Wirtschaftsforschung, Germany	Socio-economic^{Qn}	ICS	Foyer Amélioré au Sénégal by Senegalese Ministry of Energy and GTZND	Not specified (253^{sz})	Peer-reviewed	2015	Relative Advantage
Obeng et al. [71]	Energy for Sustainable Development	Science Direct	Ghana, selected communities in Northern, Upper east region, Upper west, Volta and Greater Accra regions	17	Kwame Nkrumah University of Science and Technology, Ghana	Socio-economic, Technical and Environmental^{Qn}	Solar	Variety of donor-funded public-private partnershipND	1MWp (national, 96^{sz})	Peer-reviewed	2008	Relative Advantage
Jagger and Jumbe [36]	Energy policy	Science Direct	Malawi, Kasungu and Machinga districts	7	University of North Carolina, U.S.A.	Socio-economic^{Qn}	ICS	Government of Malawi ICS program^{N}	2 million by 2020 (national, 400^{sz})	Peer-reviewed	2016	Compatibility
Mengistu et al. [75]	Renewable Energy	Science Direct	Ethiopia, Ofla, Tigray regional state and Mecha, Amhara regional state	7	Addis Ababa University, Ethiopia	Socio-economic^{B}	Biogas	National Biogas Programme Ethiopia^{N}	8063 by 2013 (national, 15sz)	Peer-reviewed	2016	Relative Advantage, Compatibility,

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Table A1 (*continued*)

Reference articles	Journals	Databases	Study areas	Number of citations	Lead institutions	Theoretical frameworks	RTech	Dissemination programs	Number of RTech disseminated	Document type	Year of publ.	Innovation attribute identified
Crossland et al. [39]	Renewable Energy	Science Direct	Rwanda, Ruhengeri, Rusumo, a village near Lake Mugasera and another village near Lake Muhazi.	8	Durham University, U.K.	Socio-technical[Ql]	Solar PV	Vision 2020 Government of Rwanda and donor partnership solar program[ND]	Solar PV installed in 300 schools between 2009 and 2012 (10[sz])	Peer-reviewed	2015	Compatibility
Adaramola [73]	International Journal of Electrical Power & Energy Systems	Science Direct	Nigeria, Jos, Plateau state	26	Norwegian University of Life Sciences, Norway	Techno-economic[Qn]	Solar PV	Not specified	Not specified	Peer-reviewed	2014	Compatibility
Tumwesige et al. [50]	Biomass and Bioenergy	Science Direct	Uganda	13	Makerere University, Uganda	Technical[Ql]	Biogas	N/A	N/A	Peer-reviewed	2014	Compatibility
Makame [77]	Management of Environmental Quality: An international journal	Emerald Insight	Tanzania, Zanzibar	8	State University of Zanzibar, Tanzania	Diffusion of Innovation Theory, Socio-economic[B]	ICS	Not specified	Not specified	Peer-reviewed	2007	Compatibility
Njenga et al. [78]	Journal of Cleaner Production	Science Direct	Kenya, Kibugu, Embu County	0	World Agroforestry Centre, Kenya	Technical and Environmental[Qn]	ICS	N/A	N/A	Peer-reviewed	2016	Compatibility
Silk et al. [80]	BMC Public Health	Springer	Kenya, Nyanza Province	8	National Center for Immunization and Respiratory Diseases, U.S.A.	Socio-economic[Qn]	ICS	Safe Water, AIDS Project and Nyando Integrated Child Health and Education Partnership Project[D]	Not specified (1500[sz])	Peer-reviewed	2012	Compatibility
Sovacool et al. [48]	Renewable Energy	Science Direct	Kenya	9	Aarhus University, Denmark	Economics[Ql]	Biogas	International Fund for Agricultural Development (IFAD) pilot program[D]	500 (national)	Peer-reviewed	2015	Compatibility
Orr et al. [82]	Experimental Agriculture	Cambridge Core	Malawi, Balaka district, Southern region	8	International Crops Research Institute for the Semi-Arid Tropics, Kenya	Socio-economic[Qn]	ICS	The Integrated Food Security Programme[D]	Over 10,000 by 2004 (in study area)	Peer-reviewed	2015	Relative Advantage
Barrie and Cruickshank [29]	Energy Policy	Science Direct	Central East Africa	0	University of Cambridge, Centre for Sustainable Development, UK	Diffusion of Innovation Theory[Ql]	Solar PV	Pay as You Go Solar Home System Project[P]	1376 by 2014	Peer-reviewed	2017	Relative Advantage
Okello et al. [66]	Journal of Power and Energy	Sage Journals	Kenya, Kisumu	2	Practical Action, Kenya	Socio-economic[Ql]	Solar PV and ICS	Disseminated by authors	4[sz]	Peer-reviewed	2013	Relative Advantage
Adkins et al. [65]	Energy Policy	Science Direct	Malawi, Mwandama	58	Columbia University, Earth Institute and the School of Engineering and Applied Science, U.S.A.	Socio-economic[Qn]	Solar PV	The Millennium Villages Project[D]	400,000 households in 80 Villages across ten Sub-Saharan countries (53[sz])	Peer-reviewed	2010	Relative Advantage
Ellegard et al. [74]	Renewable Energy	Science Direct	Zambia	34	Stockholm Environment Institute, Sweden	Economics[Qn]	Solar PV	Photovoltaic-energy service company Project, Ministry of Energy Lusaka[N]	Not specified	Peer-reviewed	2004	Compatibility

N/A = Not available, Ql = Qualitative research, Qn = Quantitative research, B = both qualitative and quantitative methods were used, sz = sample size using RTech studied, D = Donors, N = National government, ND = National government and donor partnership and P = Private sector project.

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